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# Guidelines for the Use of Life Cycle Cost Analysis on MTO Freeway Projects

MERO-018

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| Abstract | The Ministry of Transportation of Ontario (MTO) has been conducting life cycle cost analysis (LCCA) of pavement designs since the early 1970's, instituting a formal set of procedures in 1987. In 1997, an independent consultant team carried out a comprehensive review of the ministry's LCCA process for the selection of freeway pavement designs. The review was coordinated by a steering committee with members from MTO and the concrete and asphalt industries. The two-year study, completed in December 1998, recommended some changes to the LCCA procedures. On the recommendation of the asphalt and concrete industries, a follow-up study on the benefits of new technologies and their impact on LCCA was completed in December, 2000. These two reports by ERES, Fugro-BRE and ADI Consultants, Review of Life-Cycle Costing Analysis Procedures (Dec. 1998) and Benefits of New Technologies and their Impact on Life Cycle Models (Dec. 2000) form the basis for these guidelines. |
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**March 2005**

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# Executive Summary

In 1997, the Ontario Ministry of Transportation (MTO) hired an independent consultant team to carry out a comprehensive review of the ministry's Life Cycle Cost Analysis (LCAA) process for the selection of freeway pavement designs. The two resulting reports by ERES, Fugro-BRE and ADI Consultants, *Review of Life-Cycle Costing Analysis Procedures* (Dec. 1998) and *Benefits of New Technologies and their Impact on Life Cycle Models* (Dec. 2000) form the basis for these guidelines.

LCCA on high-volume roadways with greater than 1 million ESALs per year (current or projected within 5 years), all freeways and 400 series highways, and for all concrete pavements (any facility type) shall be carried out according to these guidelines.

LCCA shall compare the life cycle costs of at least one asphalt pavement design and one concrete pavement design. For each design, the life cycle costs for a 1-km long, 6-lane wide freeway pavement (3 lanes in each direction) or 1-km long, 4-lane wide (2 lanes in each direction if appropriate) are calculated. The total present worth (PW) cost of each pavement design is calculated by summing the cost of initial construction, the PW costs of individual preventive and rehabilitation activities, and the PW salvage benefit. A discount rate of 5.3% and a 50-year analysis period are stipulated. It is recommended that a probabilistic LCCA approach be used since it more realistically represents the uncertainty and variability of highway construction and pavement performance. Recommended service lives and typical preventive and rehabilitation strategies and timings for the two main freeway designs (deep strength asphalt pavement and doweled jointed plain concrete pavement) are summarized in these guidelines.

# Introduction

The Ministry of Transportation of Ontario (MTO) has been conducting Life Cycle Cost Analysis (LCCA) of pavement designs since the early 1970's, instituting a formal set of procedures in 1987. In 1997, an independent consultant team carried out a comprehensive review of the ministry's LCCA process for the selection of freeway pavement designs. The review was coordinated by a steering committee with members from MTO and the concrete and asphalt industries. The two-year study, completed in December 1998, recommended some changes to the LCCA procedures. On the recommendation of the asphalt and concrete industries, a follow-up study on the benefits of new technologies and their impact on LCCA was completed in December, 2000. These two reports by ERES, Fugro-BRE and ADI Consultants, *Review of Life-Cycle Costing Analysis Procedures* (Dec. 1998) and *Benefits of New Technologies and their Impact on Life Cycle Models* (Dec. 2000) form the basis for the following guidelines.

In 2001, MTO initiated the Alternative Bid (AB) process for freeway paving contracts. AB contracts allow contractors to bid on either an asphalt or a concrete pavement design. The bids incorporate an adjustment factor based on the MTO Life Cycle Costing model, allowing for selection of the most cost effective, long-term pavement design.

# Life Cycle Cost Analysis

LCCA is an economic analysis technique that allows comparison of design alternatives with different cost streams. LCCA involves estimating all costs associated with each alternative over a selected analysis period and converting these costs to economically comparable values.

The accuracy of LCCA results depends on the accuracy of each of the inputs, which typically include:

- Initial construction costs
- Initial pavement service life
- Rehabilitation costs
- Timing and service life of rehabilitation
- Preventive treatment costs
- Timing and service life of preventive treatment
- Discount rate
- Salvage value
- User costs (not currently considered in the MTO LCCA).

In addition, the analysis period over which all costs are summarized affects the LCCA.

Once the input parameters have been estimated, the process of calculating the life cycle cost is straightforward. It is important to note, however, that errors in predicting any of the inputs will result in errors in the LCCA. Since all of the inputs are estimates and therefore probabilistic in nature (e.g., time to first rehabilitation may occur over a range of years, the bid cost of a given material is uncertain, etc.), the resulting LCCA value is only an estimate of the actual LCCA value and is itself probabilistic.

# Components of Life Cycle Cost Analysis

## PRESENT WORTH CALCULATION

The LCCA output most used for pavement design is present worth (PW). The PW of a design alternative is the sum of all costs associated with that design, discounted to today's dollars. PW determinations are sensitive to the following factors:

- Selected discount rate
- Length of analysis period
- Service life of construction/rehabilitation/preventive alternative
- Cost factors
- Salvage value.

Present worth is calculated as follows:

$$PW = C * [1/(1 + Dis)]^n$$

where:

| | | | |
|---|---|---|---|
| PW | = | PW cost, $ |
| C | = | Future cost in present-day terms, $ |
| Dis | = | Discount rate, decimal |
| n | = | Time until cost C is incurred, years. |

The total PW cost of each pavement alternative is determined by summing the cost of initial construction, the PW costs of individual preventive and rehabilitation activities, and the PW salvage benefit. The preferred pavement alternative is the one with the lowest PW cost. Appendix A gives an example of how to calculate the present worth cost of a future pavement rehabilitation treatment.

## DISCOUNT RATE

Selection of an appropriate discount rate for LCCA has been a subject of debate for years. The discount rate greatly reduces the impact of future costs, especially after long time periods. Low discount rates favor those alternatives that combine large capital investments with low preventive strategy costs, whereas high discount rates favor the reverse.

In 1998, the Ministry of Finance set the discount rate used by the MTO to convert future costs to present-day costs for LCCA at 7.0 percent. The Ministry of Finance revised the discount rate in May 2003 to 5.3 percent. It is expected that the Ministry of Finance will revise the discount rate periodically. A standard deviation of 0.52 percent can be used for probabilistic analysis.

This discount rate is a "social" discount rate, which reflects the social benefits foregone by not investing the funds elsewhere in the economy. For example, the public funds invested in a highway project could be put to other uses, which may also provide an increase in social welfare (schools, hospitals, etc.).

## ANALYSIS PERIOD

The analysis period is a specific time period over which all costs are included to compute the PW and allow comparison of pavement design alternatives. It is recommended that a 50-year analysis period be used for high-volume roadways with greater than 1 million Equivalent Single Axel Loads (ESALs) per year (current or projected within 5 years), for all freeways and 400 series highways, and for all concrete pavements (any facility type).

## SERVICE LIFE AND ACTIVITY TIMING

The estimated service life of each pavement design alternative and of subsequent rehabilitation treatments are very important factors in LCCA. The service life of a pavement is the period of time from completion of construction until the pavement condition is considered to be unacceptable, and rehabilitation or replacement is required. Historical pavement performance and rehabilitation data can be used to determine service lives for pavement designs and rehabilitation types. The estimated service life is highly probabilistic and variable, for example, performance data may show a mean life of 15 years for a particular treatment, however, the service life may range from 5 to 20 years. Appendix B summarizes the estimated service lives of selected freeway pavement designs and their associated rehabilitation treatments to be used for LCCA on ministry projects.

## COST FACTORS

A crucial component of LCCA for pavement design selection is the cost of constructing, maintaining and rehabilitating the various pavement alternatives.

### CONSTRUCTION COSTS

Construction costs are the costs for building a section of pavement in accordance with the plans and specifications. Estimation of actual project construction costs involves risk and is highly probabilistic. Key considerations should include the following:

- Include only the components of construction that are unique to each design alternative (i.e., the main lane pavement structure and shoulder pavement structure).
- Omit items that are identical in each alternative, such as subdrains.
- Use an appropriate source to obtain construction costs (i.e., historical projects and bids, current bids, HiCo).
- Take great care in generating costs for designs that incorporate new materials or techniques for which historical information is unavailable.
- If possible, identify project-specific aspects that might affect costs, such as traffic control costs.

## PREVENTIVE TREATMENT COSTS

Preventive treatment costs are those costs associated with maintaining a pavement (surface, shoulders and drainage) at or above some predetermined performance level. The Ministry anticipates specific preventive treatments to occur at certain intervals over the life of a pavement. Preventive treatment costs can be estimated based on previous experience and historical cost data. These costs depend on pavement deterioration and operational factors that are highly probabilistic.

The cost of routine maintenance, the day-to-day activities performed to address safety and operational concerns, represents only a very small percentage of the total LCC. Also, the differences in routine maintenance costs among different pavement types are not substantially large. It is therefore recommended that routine maintenance activities be excluded from LCCA.

## REHABILITATION COSTS

Rehabilitation costs cover the activities performed as part of rehabilitating or restoring the pavement. Rehabilitation occurs when pavement problems are severe and extensive, typically requiring overlays and/or reconstruction. Rehabilitation costs are determined for each design alternative by identifying the most appropriate or most likely rehabilitation activities and their timing, and using the best estimates of costs and service lives. All of these estimates are subject to variation and are probabilistic in nature.

## ESTIMATING COSTS

Good unit price estimates are needed to ensure a fair assessment of life cycle costs. Several sources of cost data are available at MTO to determine the construction, rehabilitation and preventive treatment unit costs for use in LCCA. These sources include the MTO Highway Costing (HiCo) database, the MTO Estimating Office and the MTO Maintenance Office. The MTO HiCo database is the most readily available source of unit cost information. Costs representing the average of the three lowest bid prices for each contract for the past 5 years can be obtained. It is important to note that unit costs will vary significantly based on item quantities. For example, aggregate availability may have a major impact on costs and the impact of this should be assessed in conjunction with MTO Aggregates Units.

In the life cycle costing review carried out by ERES Consultants, the MTO project value system (PVS) database (now HiCo) was searched for cost information on selected items. As an example of cost inputs required for LCCA, Appendix C lists the items and the associated costs that were selected from the MTO PVS database for the initial construction, rehabilitation and preventive activities. The cost given for each item is the average unit cost, based on the three lowest bids for each project over a 5-year period ending in 1998.

## SALVAGE VALUE

Salvage value represents the economic value of a pavement at the end of the analysis period. Salvage value is used in LCCA so that various design alternatives may be compared equitably over the specified analysis period. The Prorated Life method is used in the MTO's LCCA procedure.

The salvage value at the end of the analysis period is determined by dividing the remaining life of the last rehabilitation treatment, by the expected life of that treatment. The result is then multiplied by the cost of the last rehabilitation. The basic equation used is as follows:

$$SV = (L_{rem}/L_{exp}) * C_{pvt}$$

where: $SV$ = Salvage value, $
$L_{rem}$ = Remaining life of last rehabilitation treatment, years
$L_{exp}$ = Expected life of last rehabilitation treatment, years
$C_{pvt}$ = Cost of final rehabilitation treatment, $.

The resulting salvage value is then converted to a PW benefit. Appendix D presents an example of how to calculate salvage value. Because the salvage value exists at the end of the analysis period, its contribution to the total LCCA is very limited, particularly when high discount rates or long analysis periods are used.

## USER COSTS

MTO currently does not consider user costs in LCCA. An argument could be made that the increase in user cost related to an increase in pavement roughness and the user delay during rehabilitation should be considered in LCCA. User cost models do exist, however the selection and implementation of a user cost model would require significant effort by MTO to calibrate to Ontario conditions. The Asset Management Group at MTO is currently assessing the issue of road user costs. Changes to the MTO LCC model may be made in the future to accommodate user costs.

## DETERMINISTIC LCCA

The deterministic LCCA approach uses only the recommended mean values for all input parameters (i.e., discount rate, costs, service lives, timings) to develop a mean overall LCC. Uncertainties and variations in estimation are not accounted for when determining which pavement type to use on a given project.

## PROBABILISTIC LCCA

A probabilistic-based LCCA uses mean and standard deviation values to define a probability distribution for a given input parameter. One input is allowed to vary according to a defined distribution (e.g., normal, uniform, exponential) while holding all other inputs at their mean value and computing the PW for each input. This is repeated many times and the PW computed each time until sufficient runs have been made to establish the expected distribution of PW. The range and shape of this distribution represents the impact or sensitivity of one input on the PW.

It is recommended that a probabilistic LCCA approach be used for high-volume roadways with greater than 1 million ESALs per year (design lane, current or projected within 5 years), for all freeways and 400 series highways, and for all concrete pavements (any facility type), since it more realistically represents the uncertainty and variability of highway construction and pavement performance.

The probabilistic approach can be carried out using a statistical software package such as Crystal Ball® developed by Decisioneering Inc. Normal probability distributions are assigned to the following inputs, using the recommended mean and standard deviation values for:

- Discount rate
- Unit costs of individual pay items
- Service lives of each initial pavement type
- Service lives of each rehabilitation type.

As Crystal Ball® performs up to 1000 iterations, a record is kept of how many times each pavement alternative has the lowest total LCC. This allows selection of the alternative with the lowest LCC and the least risk.

Recommended input values for Probabilistic LCCA on freeway projects are given in Appendix E.

# Alternative Bid Criteria

In 2001, MTO initiated the Alternative Bid (AB) process for freeway paving contracts. AB contracts allow contractors to bid on either an asphalt or a concrete pavement design. The bids incorporate an adjustment factor based on the MTO Life Cycle Costing model, allowing for selection of the most cost effective, long-term pavement design.

AB contracts are used for all new and full depth reconstruction projects in the order of five 2-lane kilometres or longer in length, where close to one million or more ESALs are anticipated in the design lanes within 5 years of construction. Projects that do not meet the set criteria are not automatically discounted, but an assessment is made on the merits of awarding them as AB contracts.

AB contracts require the preparation of two pavement designs, one asphalt and one concrete, and two sets of contract documents. Under the AB process, bidders determine their "Construction Bid" for a concrete or asphalt pavement design option. The bidder then adds a "Bid Adjustment Factor", included in the tender documents, to their Construction Bid. The Bid Adjustment Factors for the concrete and asphalt pavement options are calculated by MTO in advance, based on the MTO life cycle costing model. The lowest "Total Adjusted Bid" wins.

# MTO LCCA Procedure For Freeway Pavements

For freeway pavements with one million or more ESALs per year, LCCA is used to compare the costs of at least one asphalt pavement design and one concrete pavement design. Only the in-place cost of pavement layers in the main lanes are included in the analysis, although shoulder costs may be added if the shoulder designs of the competing alternatives differ.

The total life cycle cost is calculated by determining the cost of a 1-km long, 6-lane wide freeway pavement (3 lanes in each direction), expressed as the cost of construction, plus the PW cost of preventive and rehabilitation treatments, and the salvage benefit, over a 50 year analysis period, using a 5.3 % discount rate. Where a freeway is only four lanes wide, a 1-km long, 4-lane section shall be used.

The ERES reports consider two generic pavement types for use in new construction or reconstruction of high-volume freeways. These pavement types are doweled jointed plain concrete (JPC) and deep-strength asphalt concrete (DSAC). An overview of the travel-lane pavement structures of each generic pavement type is as follows:

Doweled JPC
250 mm PCC
100 mm Open-Graded Drainage Layer (OGDL)*
100 mm Granular A

* It may be possible to substitute Granular O for OGDL in areas with lower traffic volumes and good drainage.

DSAC
40 mm Dense Friction Course (DFC) or Stone Mastic Asphalt (SMA)
80 mm Heavy Duty Binder Course (HDBC)
200 mm Hot-Mix HL-8
100 mm OGDL*
100 mm Granular A
450 mm Granular B

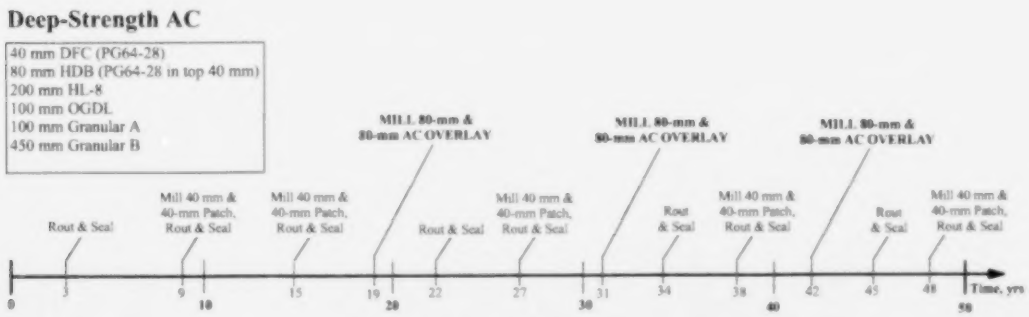
In their review of LCCA procedures, ERES Consultants looked at historical pavement performance and rehabilitation data and carried out pavement failure analyses to determine service lives for major rigid and flexible pavement designs and rehabilitation types. These service lives were further modified by a review of new technologies (smoothness specifications, end result specifications, HDBC, perpendicular transverse joints in concrete, performance graded asphalt cement, OGDL and SMA) and their impact on life cycle costing. Appendix F presents a summary of service life and preventive and rehabilitation timings for the selected freeway designs.

Historical traffic data was also used in the pavement service life analyses. For traffic loading equivalency purposes, the service life projections were based on an initial 2 million ESALs/year for flexible pavements and 3 million ESALs/year for rigid pavements with a 3.4 percent compound ESAL growth rate.

## INITIAL PERFORMANCE AND REHABILITATION OF FLEXIBLE PAVEMENTS

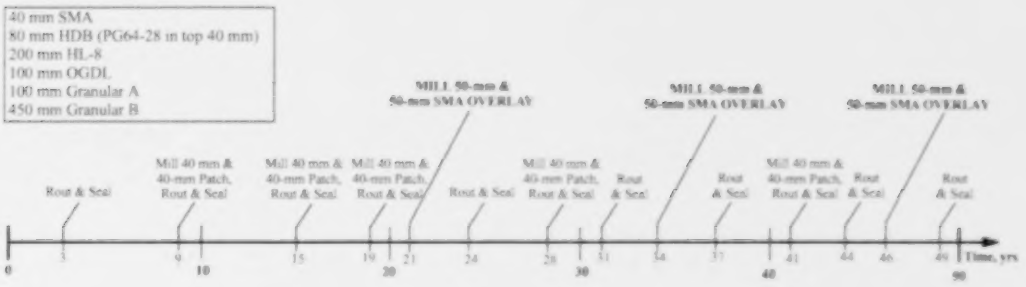
ERES Consultants used MTO pavement performance records and performance models to establish a mean initial service life for the major flexible pavement design used on Ontario freeways. The service life was further modified by the review of new technologies. Based on the analysis, an initial service life of 19 years with a standard deviation of 3.0 years is recommended for DSAC with a DFC surface. An initial life of 21 years with a standard deviation of 5.0 years is recommended for DSAC with an SMA surface.

Since the original DFC pavement is expected to last an average of 19 years, it is recommended that the first rehabilitation occur at Year 19. The mean service life of the first major AC overlay (i.e., mill 80 mm and 80-mm overlay) is expected to be 12 years, with a standard deviation of 2.8 years. To compensate for continued traffic growth over time, the average service lives of second and third resurfacings were estimated to be 11 and 10 years, respectively, with a 2.8-year service life standard deviation. In terms of the overall rehabilitation timeline, over a 50-year analysis period, resurfacing is projected to occur in Years 19, 31 and 42.




Since the original SMA pavement is expected to last an average of 21 years, it is recommended that the first rehabilitation occur at Year 21. The mean service life of the first major AC overlay (i.e., mill 50 mm and 50-mm SMA overlay) is expected to be 13 years, with a standard deviation of 2.8 years. The average service lives of second and third resurfacings were estimated to be 12 and 11 years respectively, with a 2.8-year service life standard deviation. In terms of the overall rehabilitation timeline, over a 50-year analysis period, resurfacing is projected to occur in Years 21, 34 and 46.

**Deep-Strength AC**




The rehabilitation quantities for a 1-km long, 6-lane wide Deep Strength Asphalt Pavement for both a DFC and SMA surface are presented in Appendix G.

## PREVENTIVE STRATEGIES FOR FLEXIBLE PAVEMENTS

Rout-and-seal operations should be planned 3 years after original flexible pavement construction and 3 years after each subsequent AC overlay. A second rout-and-seal application should be performed a few years later in conjunction with selected resurfacing. In the originally constructed pavement, a third rout-and-seal operation combined with selected resurfacing is recommended for Year 15.

Over a 50-year analysis period, the Ministry's typical preventive strategy for flexible pavements with a DFC surface includes rout-and-seal cracks at Years 3, 9, 15, 22, 27, 34, 38, 45 and 48, and selective resurfacing (i.e. 40-mm mill-and-patch) at Years 9, 15, 27, 38 and 48.

For flexible pavements with an SMA surface, rout-and-seal cracks is scheduled for Years 3, 9, 15, 19, 24, 28, 31, 37, 41, 44 and 49, with selective resurfacing (i.e. 40-mm mill-and-patch) at Years 9, 15, 19, 28 and 41.

The preventive strategy quantities for a 1-km long, 6-lane wide Deep Strength Asphalt Pavement for both a DFC and SMA surface are presented in Appendix G.

## INITIAL PERFORMANCE AND REHABILITATION OF RIGID PAVEMENTS

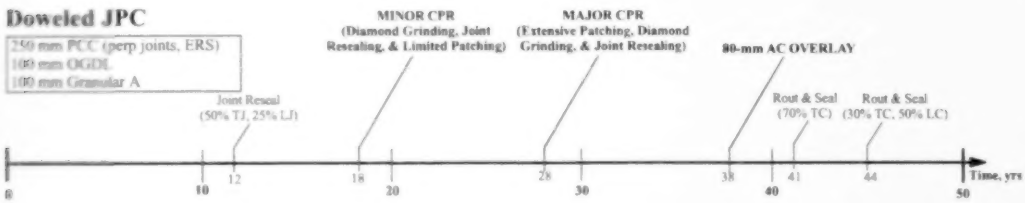
ERES Consultants used calibrated performance prediction models and failure analysis using actual MTO pavement performance data to estimate the service life of newly constructed rigid pavements. This analysis was supplemented by a review of perpendicular transverse joint performance and a 1998 diamond grinding study in the United States.

It is recommended that diamond grinding to improve friction of JPC pavements be scheduled for 18 years after construction, with a standard deviation of 2.5 years. Based on performance reviews in the U.S., a mean service life of 10 years is recommended for the diamond grinding with a standard deviation of 1.5 years.

Analysis of the JPC design indicated that the structural life of JPC should be 34 years. However, to address critical losses of surface friction and joint seal effectiveness, and to repair a significant amount of spalled joints, it was determined that major rehabilitation of JPC in the form of concrete pavement restoration (CPR) would be most appropriate in Year 28, with a standard deviation of 4.0 years. CPR would include full- and partial-depth repairs, including some slab replacements, diamond grinding, and joint resealing. The expected service life of CPR is 10 years with a standard deviation of 2.0 years.

With CPR projected for Year 28 and estimated to last for 10 years, the first AC overlay on JPC is scheduled for Year 38. The recommended service life for first AC overlays (80-mm AC overlay) placed on JPC pavement is 12 years with a standard deviation of 2.3 years.

The rehabilitation quantities for a 1-km long, 6-lane wide Doweled JPC pavement are presented in Appendix G.




## PREVENTIVE STRATEGIES FOR RIGID PAVEMENTS

For doweled JPC pavement, it is recommended that the initial joint resealing operation occur in Year 12, with resealing operations recommended for Years 18 and 28. Rout-and-sealing cracks in the first AC overlay is scheduled to occur in Year 41 and 44. The preventive strategy quantities for a 1-km long, 6-lane wide Deep Doweled JPC pavement are presented in Appendix G.

# Conclusions

Life Cycle Costing Analysis on high-volume roadways with greater than 1 million ESALs per year (current or projected within 5 years), all freeways and 400 series highways, and for all concrete pavements (any facility type) shall be carried out according to the following:

1) Compare the life cycle costs of at least one asphalt pavement design and one concrete pavement design.

2) For each design, calculate the life cycle costs for a 1-km long, 6-lane wide freeway pavement (3 lanes in each direction) or 1-km long, 4-lanes wide (2 lanes in each direction) if appropriate.

3) When estimating costs, include only the main lane pavement structure. Omit items that are identical in each alternative. Use an appropriate source to obtain costs (i.e., HiCo).

4) Calculate the total PW cost of each pavement design by summing the cost of initial construction, the PW costs of individual preventive and rehabilitation activities, and the PW salvage benefit.

$$PW = C * [1/(1 + Dis)]^n$$

where:
- PW = PW cost, $
- C = Future cost in present-day terms, $
- Dis = Discount rate, decimal
- n = Time until cost C is incurred, years.

5) Use a discount rate of 5.3 %, with a standard deviation of 0.52 % for probabilistic analysis.

6) Use a 50-year analysis period.

7) Calculate salvage value by dividing the remaining life of the pavement at the end of the analysis period by the expected life of the pavement, and multiplying by the initial cost of the final pavement rehabilitation. The basic equation used is as follows:

$$SV = (L_{rem}/L_{exp}) * C_{pvt}$$

where:
- SV = Salvage value, $
- $L_{rem}$ = Remaining life of pavement, years
- $L_{exp}$ = Expected life of pavement, years
- $C_{pvt}$ = Cost of final pavement rehabilitation, $.

8) It is recommended that a probabilistic LCCA approach be used since it more realistically represents the uncertainty and variability of highway construction and pavement performance. Probablistic LCCA also determines the amount of overlap between competing designs. The probabilistic approach can be carried out using Crystal Ball® software. Probabilistic LCCA uses mean and standard deviation values and a normal probability distribution for each input. The recommended mean and standard deviation values for discount rate, unit costs, and service lives should be used for freeway pavement designs. The average adjustment cost determined by the probabilistic analysis should be used in the LCCA.

9) Recommended service lives and typical preventive and rehabilitation strategies and timings for the two main freeway designs (deep strength asphalt pavement and doweled jointed plain concrete pavement) are summarized below:

| Typical Construction Alternatives & Service Lives | Typical Rehabilitation Strategies | Typical Preventive Strategies |
|---|---|---|
| DSAC:<br>• 19 yr service life for DFC<br>• 21 yr service life for SMA<br>Doweled JPC:<br>• 28 yr service life | DSAC:<br>• mill & resurface @ 19, 31, and 42 yrs for DFC<br>• mill & resurface @ 21, 34 and 46 yrs for SMA.<br>Doweled JPC:<br>• diamond-grind @ 18 yr, CPR @ 28 yr, resurface @ 38 yr | DSAC:<br>• rout & seal cracks @ 3, 9, 15, 22, 27, 34, 38, 45 and 48 yrs, with selective mill & patch @ 9, 15, 27, 38 and 48 yrs for DFC<br>• rout & seal cracks @ 3, 9, 15, 19, 24, 28, 31, 37, 41, 44 and 49 yrs, with selective mill & patch @ 9, 15, 19, 28 and 41 yrs for SMA.<br>Doweled JPC:<br>• joint resealing @ 12, 18, and 28 yrs, rout & seal AC overlay @ 41 and 44 yrs |

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# Appendix A: Present Worth Example

## CALCULATING THE PRESENT WORTH (PW) COST OF A FUTURE REHABILITATION

The PW of a design alternative is the sum of all costs associated with that design, discounted to today's dollars. Present worth is calculated as follows:

$$PW = C * [1/(1 + Dis)]^n$$

where:
- PW = PW cost, $
- C = Future cost in present-day terms, $
- Dis = Discount rate, decimal
- n = Time until cost C is incurred, years.

The total PW cost of each pavement alternative is determined by summing the cost of initial construction, the PW costs of individual preventive and rehabilitation activities, and the PW salvage benefit.

For example, a selected pavement design will require rehabilitation at Year 19. The rehabilitation consists of milling 80 mm and resurfacing with 40 mm DFC over 40 mm HDBC. To calculate the PW cost of the future rehabilitation activity for a pavement section 1 km long and 6 lanes wide, first determine the future cost per km based on recommended quantities and unit costs.

| Treatment | Quantity | Unit Cost | Future Cost/km |
|---|---|---|---|
| Mill 80mm asphalt pavement | 4532 t | $9.65 | $43,733.80 |
| Resurface DFC-40mm | 2288 t | $65.40 | $149,635.20 |
| HDB-40mm | 2156 t | $43.10 | $92,923.60 |

Then discount the future costs incurred in Year 19 to PW costs using a discount rate of 5.3%:

$$PW = C * [1/(1 + 0.053)]^{19}$$

The resulting PW costs are summarized below:

| Treatment | Future Cost/km | Present Worth Cost |
|---|---|---|
| Mill 80mm asphalt pavement | $43,733.80 | $16,394 |
| Resurface DFC-40mm | $149,635.20 | $56,091 |
| HDB-40mm | $92,923.60 | $34,833 |

# Appendix B: Recommended Initial and Rehabilitation Service Lives For Freeway LCCA

| Initial Pavement Type | Recommended Estimate of Initial Service Life, years | |
|---|---|---|
| | Mean | Standard Deviation |
| Deep Strength Asphalt Pavement (DSAC) | 19 (DFC)<br>21 (SMA) | 3.0 (DFC)<br>5.0 (SMA) |
| Doweled Jointed Plain Concrete (JPC) | 18 (functional)<br>28 (structural) | 2.5 (functional)<br>4.0 (structural) |
| **Rehabilitation Activity** | **Recommended Estimate of Rehabilitation Service Life, years** | |
| | **Mean** | **Standard Deviation** |
| First AC overlay (mill 80 mm and 80-mm overlay) on DSAC with DFC surface | 12 | 2.8 |
| Second AC overlay (mill 80 mm and 80-mm overlay) on DSAC with DFC surface | 11 | 2.8 |
| Third AC overlay (mill 80 mm and 80-mm overlay) on DSAC with DFC surface | 10 | 2.8 |
| First AC overlay (mill 50 mm and 50-mm overlay) on DSAC with SMA surface | 13 | 2.8 |
| Second AC overlay (mill 50 mm and 50-mm overlay) on DSAC with SMA surface | 12 | 2.8 |
| Third AC overlay (mill 50 mm and 50-mm overlay) on DSAC with SMA surface | 11 | 2.8 |
| Surface retexturing of JPC | 10 | 1.5 |
| CPR (patching, diamond grinding, and joint resealing) of JPC | 10 | 2.0 |
| First AC overlay (80 mm) on JPC | 12 | 2.3 |

# Appendix C: Unit Costs (From 1998 ERES Report)

| Pay Item | Unit of Measure | Recommended Unit Costs (1998) (Mean ± Std. Dev.), $ |
|---|---|---|
| PCC Surface (25 MPa) | $m^2$ | 35.80±3.60 |
| PCC Base (25 MPa) | $m^2$ | 34.25±3.45 |
| PCC Surface (30 MPa) | $m^2$ | 36.35±3.65 |
| PCC Base (30 MPa) | $m^2$ | 34.75±3.50 |
| Load Transfer Devices | m | 23.70±1.75 |
| Hot-Mix HL-2 | t | 37.50±3.75 |
| Hot-Mix HL-8 | t | 38.50±4.35 |
| Heavy-Duty Binder Course | t | 41.10±4.45 |
| Open Friction Course (25 mm) | t | 74.70±11.40 |
| Dense Friction Course | t | 63.40±2.40 |
| Open-Graded Drainage Layer | t | 35.40±3.35 |
| Tack Coat | $m^2$ | 0.19±0.06 |
| Pipe Subdrains | m | 15.60±2.30 |
| Granular A | t | 10.25±1.65 |
| Granular B, type I | t | 7.15±1.55 |
| Diamond Grinding PCC Surface | $m^2$ | 5.75±0.60 |
| Partial-Depth PCC Repair | $m^2$ | 205.50±20.55 |
| Full-Depth PCC Repair | $m^2$ | 157.30±31.40 |
| Bituminous Patches to Spalls | $m^2$ | 160.35±35.85 |
| PCC Joint Resealing | m | 7.05±0.70 |
| Unbonded Concrete Overlay | $m^3$ | 88.50±8.85 |
| Rout and Seal Cracks in PCC | m | 5.90±1.25 |
| Rout and Seal Cracks in AC | m | 1.80±0.20 |
| Mill 80 mm AC Surface | t | 9.65±4.65 |
| Selective Resurfacing (mill 40 mm & patch 40 mm DFC) | $m^2$ | 6.65±0.65 |

# Appendix D: Salvage Value Example

## CALCULATION OF SALVAGE VALUE

Salvage value is determined at the end of the analysis period by dividing the remaining life of the last rehabilitation treatment by the expected life of the last rehabilitation treatment, and multiplying by the cost of the last rehabilitation.

The basic equation used is as follows:

$$SV = (L_{rem}/L_{exp}) * C_{pvt}$$

where:
- $SV$ = Salvage value, $
- $L_{rem}$ = Remaining life of last rehabilitation treatment, years
- $L_{exp}$ = Expected life of last rehabilitation treatment, years
- $C_{pvt}$ = Cost of last rehabilitation treatment, $.

For example, a pavement needs an AC overlay at 45 years and the overlay is expected to last 10 years. The cost of the overlay at Year 45 is $400,000. At the end of a 50-year analysis period, the remaining life of the AC overlay is 5 years. Thus, the salvage value of the AC overlay is computed as follows:

$$SV = (5 \text{ years}/10 \text{ years}) * \$400{,}000$$
$$SV = \$200{,}000$$

The resulting salvage value is then converted to a PW benefit using a discount rate of 5.3% and an analysis period of 50 years.

$$PW = \$200{,}000 * (1/1.053)^{50} = \$15{,}122$$

# Appendix E: Input Values for Probabilistic LCCA of Freeway Pavements

| LCCA Input Parameter | Mean | Standard Deviation |
|---|---|---|
| Discount Rate, % | 5.3 | 0.52 |
| Life of JPC to first minor rehabilitation (surface texturing), years | 18.0 | 2.5 |
| Life of diamond grinding of JPC, years | 10.0 | 1.5 |
| Life of JPC to first major rehabilitation (CPR), years | 28.0 | 4.0 |
| Life of CPR of JPC, years | 10.0 | 2.0 |
| Life of first AC overlay on JPC, years | 12.0 | 2.3 |
| Life of DSAC with DFC surface to first major rehabilitation, years | 19.0 | 3.0 |
| Life of first AC overlay on DSAC with DFC surface, years | 12.0 | 2.8 |
| Life of second AC overlay of DSAC with DFC surface, years | 11.0 | 2.8 |
| Life of third AC overlay of DSAC with DFC surface, years | 10.0 | 2.8 |
| Life of DSAC with SMA surface to first major rehabilitation, years | 21.0 | 5.0 |
| Life of first AC overlay on DSAC with SMA surface, years | 13.0 | 2.8 |
| Life of second AC overlay of DSAC with SMA surface, years | 12.0 | 2.8 |
| Life of third AC overlay of DSAC with SMA surface, years | 11.0 | 2.8 |
| 250-mm JPC, $/m$^2$ | 35.00 | 3.50 |
| 250-mm JPC base, $/m$^2$ | 34.25 | 3.45 |
| Load transfer devices, $/m | 23.70 | 1.25 |
| Open graded drainage layer, $/t | 35.40 | 3.35 |
| Dense friction course, $/t | 63.40 | 2.40 |
| Heavy duty binder, $/t | 41.10 | 4.45 |
| HL-8, $/t | 38.50 | 4.35 |
| Granular A, $/t | 10.25 | 1.65 |
| Granular B, $/t | 7.15 | 1.55 |
| Joint resealing, $/m | 6.50 | 0.65 |
| Diamond grinding, $/m$^2$ | 5.00 | 0.50 |
| Rout-and-seal (AC), $/m | 1.80 | 0.20 |
| Tack Coat, $/m$^2$ | 0.19 | 0.06 |
| Mill 40 mm and patch with 40 mm DFC, $/m$^2$ | 6.25 | 0.65 |
| Mill 80 mm, $/t | 9.65 | 4.65 |
| Partial-depth PCC patching, $/m$^2$ | 205.50 | 27.50 |
| Full-depth PCC patching, $/m$^2$ | 157.30 | 31.40 |

**Costs are from 1998 and require updating on a project specific basis.**

# Appendix F: Summary of Preventive and Rehabilitation Strategies for LCCA of Freeway Pavements

| Year | DSAC with DFC Surface | DSAC with SMA Surface | Doweled JPC |
|---|---|---|---|
| 1 | | | |
| 2 | | | |
| 3 | Rout & Seal | Rout & Seal | |
| 4 | | | |
| 5 | | | |
| 6 | | | |
| 7 | | | |
| 8 | | | |
| 9 | Mill & Patch 40 mm; Rout & Seal | Mill & Patch 40 mm; Rout & Seal | |
| 10 | | | |
| 11 | | | |
| 12 | | | Joint Reseal |
| 13 | | | |
| 14 | | | |
| 15 | Mill & Patch 40 mm; Rout & Seal | Mill & Patch 40 mm; Rout & Seal | |
| 16 | | | |
| 17 | | | |
| 18 | | | Minor CPR – Diamond Grinding |
| 19 | **Mill and AC overlay 80 mm** | Mill & Patch 40 mm; Rout & Seal | |
| 20 | | | |
| 21 | | **Mill and AC overlay 50 mm** | |
| 22 | Rout & Seal | | |
| 23 | | | |
| 24 | | Rout & Seal | |
| 25 | | | |
| 26 | | | |
| 27 | Mill & Patch 40 mm; Rout & Seal | | |

| | | | |
|---|---|---|---|
| 28 | | Mill & Patch 40 mm;<br>Rout & Seal | **Major CPR** |
| 29 | | | |
| 30 | | | |
| 31 | **Mill and AC overlay 80 mm** | Rout & Seal | |
| 32 | | | |
| 33 | | | |
| 34 | Rout & Seal | **Mill and AC overlay 50 mm** | |
| 35 | | | |
| 36 | | | |
| 37 | | Rout & Seal | |
| 38 | Mill & Patch 40 mm;<br>Rout & Seal | | **80 mm AC Overlay** |
| 39 | | | |
| 40 | | | |
| 41 | | Mill & Patch 40 mm;<br>Rout & Seal | Rout & Seal |
| 42 | **Mill and AC overlay 80 mm** | | |
| 43 | | | |
| 44 | | Rout & Seal | Rout & Seal |
| 45 | Rout & Seal | | |
| 46 | | **Mill and AC overlay 50 mm** | |
| 47 | | | |
| 48 | Mill & Patch 40 mm;<br>Rout & Seal | | |
| 49 | | Rout & Seal | |
| 50 | | | |

# Appendix G. Summary of Preventive and Rehabilitation Quantities

The preventive and rehabilitation quantities for a 1-km long, 6-lane wide (3.5m + 3.75m + 3.75m) Deep Strength Asphalt Pavement with DFC surface are given below:

## DEEP STRENGTH ASPHALT PAVEMENT – DFC SURFACE

| Scheduled Maint/ Rehab Year | Preventive/ Rehabilitation Treatment | Quantities /Km | Pay Item Price, $ | Cost/Km $ | Present Worth Prev./Rehab $ (5.3% discount) |
|---|---|---|---|---|---|
| 3 | Rout and Seal cracks | 352 m | $1.80 | $634 | $543 |
| 9 | Rout and Seal cracks | 938 m | $1.80 | $1,688 | $1,061 |
| | Mill (40 mm) and 40-mm Patch | 1100 $m^2$ | $6.25 | $6,875 | $4,319 |
| 15 | Rout and Seal cracks | 1760 m | $1.80 | $3,168 | $1,460 |
| | Mill (40 mm) and 40-mm Patch | 4440 $m^2$ | $6.25 | $27,750 | $12,789 |
| 19 | **Mill 80mm asphalt pavement** | 22,000 $m^2$ | $1.50 | $33,000 | $12,370 |
| | **Resurface DFC-40mm** | 2288 t | $65.40 | $149,635 | $56,091 |
| | **HDB-40mm** | 2156 t | $43.10 | $92,923.60 | $25,694 |
| | **Tack coat – 2 layers** | 44000 $m^2$ | $0.19 | $8360.00 | $3,134 |
| 22 | Rout and Seal cracks | 352 m | $1.80 | $634 | $203 |
| 27 | Rout and Seal cracks | 1400 m | $1.80 | $2,520 | $625 |
| | Mill (40 mm) and 40-mm Patch | 2220 $m^2$ | $6.25 | $13,875 | $3,441 |
| 31 | **Mill 80mm asphalt pavement** | 22,000 $m^2$ | $1.50 | $33,000 | $6,656 |
| | **Resurface DFC-40mm** | 2288 t | $65.40 | $149,635 | $30,182 |
| | **HDB-40mm** | 2156 t | $43.10 | $92,923.60 | $18,743 |
| | **Tack coat – 2 layers** | 44000 $m^2$ | $0.19 | $8360.00 | $1,686 |
| 34 | Rout and Seal cracks | 352 m | $1.80 | $634 | $109 |
| 38 | Rout and Seal cracks | 1400 m | $1.80 | $2,520 | $354 |
| | Mill (40 mm) and 40-mm Patch | 2220 $m^2$ | $6.25 | $13,875 | $1950 |
| 42 | **Mill 80mm asphalt pavement** | 22,000 $m^2$ | $1.50 | $33,000 | $3,772 |
| | **Resurface DFC-40mm** | 2288 t | $65.40 | $149,635 | $17,102 |
| | **HDB-40mm** | 2156 t | $43.10 | $92,923.60 | $10,620 |
| | **Tack coat – 2 layers** | 44000 $m^2$ | $0.19 | $8360.00 | $955 |
| 45 | Rout and Seal cracks | 352 m | $1.80 | $634 | $62 |
| 48 | Rout and Seal cracks | 1400 m | $1.80 | $2,520 | $211 |
| | Mill (40 mm) and 40-mm Patch | 2220 $m^2$ | $6.25 | $13,875 | $1,163 |

The preventive and rehabilitation quantities for a 1-km long, 6-lane wide (3.5m + 3.75m + 3.75m) deep strength asphalt pavement with SMA surface are given below:

## DEEP STRENGTH ASPHALT PAVEMENT – SMA SURFACE

| Scheduled Maint/ Rehab Year | Preventive/ Rehabilitation Treatment | Quantities /Km | Pay Item Price, $ | Cost/Km $ | Present Worth Prev./Rehab $ (5.3%discount) |
|---|---|---|---|---|---|
| 3 | Rout and Seal cracks | 280 m | $1.80 | $504 | $432 |
| 9 | Rout and Seal cracks | 560 m | $1.80 | $1,008 | $633 |
| | Mill (40 mm) and 40-mm Patch | 1100 $m^2$ | $6.25 | $6,875 | $4,319 |
| 15 | Rout and Seal cracks | 1120 m | $1.80 | $2,016 | $929 |
| | Mill (40 mm) and 40-mm Patch | 3330 $m^2$ | $6.25 | $20,813 | $9,592 |
| 19 | Rout and Seal cracks | 1760 m | $1.80 | $3,168 | $1,188 |
| | Mill (40 mm) and 40-mm Patch | 4440 $m^2$ | $6.25 | $27,750 | $10,402 |
| 21 | **Mill 50mm asphalt pavement** | 22,000 $m^2$ | $1.50 | $33,000 | $11,156 |
| | **Resurface SMA -50mm** | 2860 t | $73.00 | $208,780 | $70,582 |
| | **Tack coat** | 22,000 $m^2$ | $0.19 | $4180 | $1,413 |
| 24 | Rout and Seal cracks | 280 m | $1.80 | $504 | $146 |
| 28 | Rout and Seal cracks | 1120 m | $1.80 | $2,016 | $475 |
| | Mill (40 mm) and 40-mm Patch | 3330 $m^2$ | $6.25 | $20,813 | $4,902 |
| 31 | Rout and Seal cracks | 560 m | $1.80 | $1,008 | $203 |
| 34 | **Mill 50mm asphalt pavement** | 22,000 $m^2$ | $1.50 | $33,000 | $5,701 |
| | **Resurface SMA -50mm** | 2860 t | $73.00 | $208,780 | $36,068 |
| | **Tack coat** | 22,000 $m^2$ | $0.19 | $4180 | $722 |
| 37 | Rout and Seal cracks | 280 m | $1.80 | $504 | $75 |
| 41 | Rout and Seal cracks | 1120 m | $1.80 | $2,016 | $243 |
| | Mill (40 mm) and 40-mm Patch | 3330 $m^2$ | $6.25 | $20,813 | $2,505 |
| 44 | Rout and Seal cracks | 560 m | $1.80 | $1,008 | $104 |
| 46 | **Mill 50mm asphalt pavement** | 22,000 $m^2$ | $1.50 | $33,000 | $3,068 |
| | **Resurface SMA -50mm** | 2860 t | $73.00 | $208,780 | $19,408 |
| | **Tack coat** | 22,000 $m^2$ | $0.19 | $4180 | $389 |
| 49 | Rout and Seal cracks | 280 m | $1.80 | $504 | $40 |

The preventive and rehabilitation quantities for a 1-km long, 6-lane wide Doweled Jointed Plain Concrete Pavement (3.5m + 3.75m + 3.75m + 0.5m pps) are given below.

## DOWELED JOINTED PLAIN CONCRETE PAVEMENT

| Scheduled Maint/ Rehab Year | Preventive/ Rehabilitation Pay Items | Quantities /Km | Pay Item Price, $ | Cost/Km $ | Present Worth Prev./Rehab$ (5.3% discount) |
|---|---|---|---|---|---|
| 12 | Reseal 50% of transverse joints and 25% of longitudinal joints | 3783 m | $6.50 | $24,590 | $13,232 |
| 18 | **Diamond Grinding** | 22000 $m^2$ | $5.00 | $110,000 | $43,419 |
| | **CPR (partial-depth PCC patching)** | 64 $m^2$ | $205.50 | $13,152 | $5,191 |
| | **CPR (full-depth PCC patching)** | 113 $m^2$ | $157.30 | $17,775 | $7,016 |
| | **Reseal 100% of transverse joints and 50% of longitudinal joints** | 7622 m | $6.50 | $49,543 | $19,556 |
| 28 | **CPR (full-depth PCC patching)** | 376 $m^2$ | $157.30 | $59,145 | $13,929 |
| | **CPR (partial-depth PCC patching)** | 213 $m^2$ | $205.50 | $43,772 | $10,309 |
| | **CPR (diamond grinding)** | 22000 $m^2$ | $5.00 | $110,000 | $25,906 |
| | **CPR (joint resealing)** | 7754 m | $6.50 | $50,401 | $11,870 |
| 38 | **Tack coat concrete surface** | 22000 $m^2$ | $0.19 | $4,180 | $587 |
| | **Resurface with DFC-40mm** | 2254 t | $63.40 | $142,904 | $20,080 |
| 41 | Rout-and-Seal 70% of transverse cracks | 3896 m | $1.80 | $7,013 | $844 |
| 44 | Rout-and-Seal 30% of transverse and 50% of longitudinal cracks | 3670 m | $1.80 | $6,606 | $681 |